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#### **Final Report**

N00014-99-1-0383

### Alternative Approaches to p-type Doping of GaN

UR Account No. 5-27979
G. W. Wicks
The Institute of Optics, University of Rochester, Rochester, NY

### 1. The problem being addressed: P-type doping of GaN

- •Conventional (column II) acceptors produce low hole concentrations.
- •High hole concentrations are needed for low resistivity p-type material and p-type ohmic contacts.

#### 2. Technical Approach: Boron doping

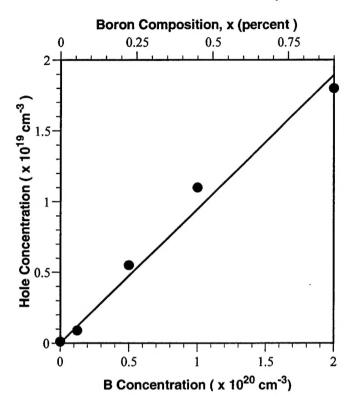
#### Background: Boron doping

III	IV	V
В		N
Al		P
Ga		As
In		Sb

# **Boron Doping in GaAs**

- •Experimental Evidence: 2 Sites for Boron
  - 1.  $B_{III}$  forms the ternary,  $B_xGa_{1-x}As$ . Bandgap increases with x (33 meV/%)
  - 2.  $B_v$  is a double acceptor. Hole concentrations >  $10^{19}$  cm<sup>-3</sup>(!) are possible.

## Hole Concentrations in Boron-doped GaAs



~5% of the boron atoms incorporate as  $B_{As}$ 

## 3. Activities in this program: Boron Doping in GaN

- •MBE Growth
  - 1. Ammonia source of nitrogen
  - 2. Plasma source of nitrogen
- •High temperature (<2200°C) Effusion Cell for Boron

#### Findings in the program

- •Boron doping of GaN does not produce p-type conductivity.
- •Boron antisite double acceptor exists in GaN, but it is too deep (~1.3 eV above valence band) to produce valence band holes.

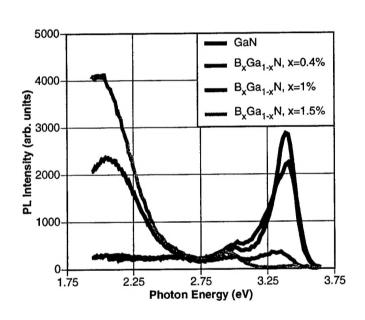
## Influence of V:III Flux Ratio on Boron Site Selection

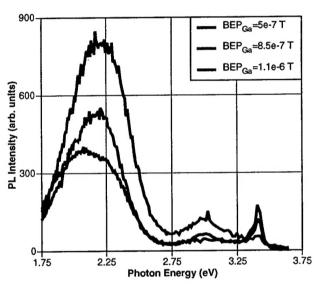
(Nitrogen flux constant for all growths)

#### Interpretation:

- •Gallium rich growth conditions enhance the formation of  $B_N$ ; Nitrogen rich growth conditions enhance the formation of  $B_{Ga}$ .
- •Increased  $B_N$  increases the compensation of the n-type background.

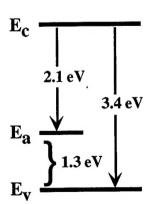
# Room Temperature Photoluminescence of B<sub>x</sub>Ga<sub>1-x</sub>N

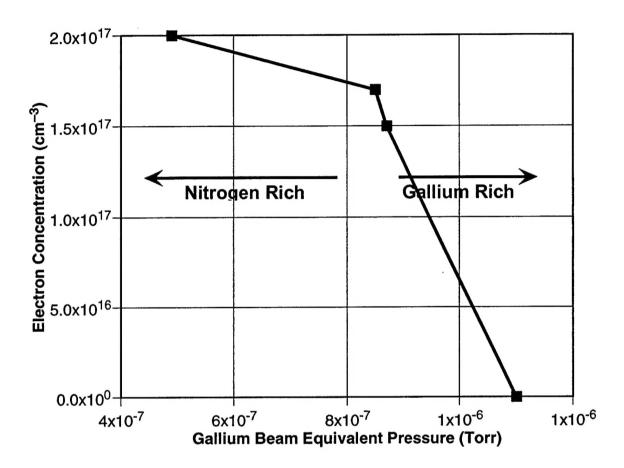




## Interpretation:

Observed PL spectra are consistent with the existence of a B acceptor level around 1.3 eV above the valence band.





- •40 GaN:B growths done (NH3 and N-plasma sources)—no p-type GaN
- •N-type conductivity ranging from:

typical high conductivity:  $n{=}10^{20}~\text{cm}^{\text{-}3}$  and  $\mu{=}12~\text{cm}^2{\text{-}v/s}$ 

to

typical low conductivity:  $n=10^{17}$  cm<sup>-3</sup> and  $\mu=90$  cm<sup>2</sup>•v/s

to

highly resistive

- •Electron concentration in GaN:B determined by:
- $\Rightarrow$ unintentional donors (oxygen and nitrogen vacancies) and  $B_{\scriptscriptstyle N}$
- $\Rightarrow$ affected by  $T_B$ , V/III,  $T_S$ , and outgasing

# Summary: GaN:B

- $\bullet$ B antisite double acceptor exists in GaN, but it is too deep ( $\sim$ 1.3 eV) to be useful for producing large hole concentrations.
- •The site occupancy of B is easily influenced by V/III
- •The B antisite double acceptor produces strong, red PL